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LONG TERM PERFORMANCE OF WIND-DRIVEN INDUCTION GENERATORS

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SUMMARY:

Five years of operational experience with wind-electric systems showed that power was produced 65% of the time and that systems were ready to operate 95% of the time. The pitch angle is a critical adjustment because it can alter the peak power by several kW and change the annual energy production by 10%.

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ABSTRACT

Most modern wind turbines which generate utility-compatible AC electric power are designed with induction generators. Wind turbines with induction generators have been operated to supply electric power for irrigation pumps at Bushland, Texas, since 1979. Turbines were 10 and 13.4 m in diameter and were rated at 25 and 40 kW.

During 5 years of operation, a turbine rated at 25 kW produced 141,111 kWh in 23,359 hours of operation, averaging 6 kW. All units averaged at least 470 hours of operation per month (64% of the time) and were available (switch-on ready to operate) between 91% for the oldest unit, and 99.9% for the newest unit. The newer unit which had a 40 kW generator, produced 49,476 kWh in 3,218 hours of operation, demonstrating that the wind industry is beginning to produce dependable efficient machines.

The Rayleigh probability distribution and power curves were used to predict annual energy production for the machines. These predictions show the importance of selecting sites with the highest average windspeed in order to prevent disappointment caused from selecting a poor site.

INTRODUCTION

Wind electric systems were used extensively during the 1930's and 40's to provide small amounts of electric power in rural areas. These units had DC generators that produced enough power to keep several batteries charged; providing electricity for lights and the radio. Rotor sizes ranged from 2 to 5 m and consisted of 2 to 4 blades (Park, 1981). Systems based on these old designs are still manufactured today.

A new era in wind energy technology began shortly after the oil embargo of 1973. New interest in wind technology stimulated improvement of old concepts and several new ideas. Most machines designed between 1975 and 1979 utilized either DC generators,

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1/ Contribution from USDA, Agricultural Research Service, Bushland, TX; in cooperation with The Alternative Energy Institute, West Texas State University, Canyon , TX.

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similar to the older ones, or an alternator using a synchronous inverter to make the power utility-compatible. Machines using either DC generators or alternators require speed regulation, normally a mechanism to vary the pitch of the rotor, so that power is limited to avoid overloading the generator. As machine size increased, the variable pitch mechanism became more complicated and costly. Beginning in 1978, two manufacturers began using induction motors, operated above synchronous speed, as generators in wind turbines. An induction generator operates essentially at a constant speed with a gearbox between the rotor and generator. The induction generator offered several advantages over the other systems; the main ones being that the pitch control system could be eliminated and that interfacing to the electric utility was greatly simplified (Park, 1981). A disadvantage of the induction generator is that it requires excitation from an external source, usually the utility line. During the early 1980's, the use of induction generators greatly increased and today about 90% of all wind systems sold are of the induction generator type.

The USDA-Agricultural Research Service began experimenting with wind systems for irrigation pumping in 1977 and acquired one of the largest induction generator systems available in 1979. A newer design, funded by the Department of Energy, using design criteria provided by USDA-ARS, was erected in 1982. This paper reports on the performance of three machines which have been producing electric power for irrigation pumps. Specifications of the machines are given in Table 1.

AERODYNAMIC PERFORMANCE

Most electrical-generating wind machines utilize aerodynamic lift to produce rotation and thus the torque needed to rotate the generator. These systems operate at a rotor tip speed to windspeed ratio, called the tip-speed ratio, between 4 to 8. Thus, the rotational speed of the rotor decreases as the diameter increases. At a given rotational speed, the amount of lift is dependent on the windspeed and the angle at which the airfoil strikes the wind. This attack angle or pitch angle becomes very important for fixed-pitch machines in determining the amount of power which can be extracted from the wind. Fig. 1 shows power curves for two different pitch settings taken from a wind turbine with a 13.4-m diameter rotor. Data, sampled at 4.5 times per second with a 15-second average, were utilized to produce the power curves, and data were corrected to an air density of 1.226 kg/m^3, which represents standard density. The curves are similar between 5 and 13 m/s windspeed and the cut-in windspeed was not affected by the change in pitch. This one-degree change increased maximum power from 42 to 46 kW and produced about a 10% increase in annual energy production.

Other studies conducted by USDA-ARS staff and cooperating universities have shown that an incorrect pitch setting can reduce maximum power by 20% and annual energy by 25% (Clark et al., 1981; Nelson et al., 1984). The optimum pitch setting is determined by using the average windspeed and a windspeed distribution. Computer models were released in 1983 by DOE which enable manufacturers to better select the optimum pitch (Tu and Kertesz, 1983).

EQUIPMENT PERFORMANCE

Wind machines contain gearboxes, brakes, and electronic controls, in addition to the rotor and generator; all of which affect performance. The wind turbines, operated at Bushland, Texas, by USDA, have experienced wind gusts in excess of 32 m/s while running and temperatures between -18 and 40° C. A Carter 25[3/] installed in 1979 had an average availability of 73%. Availability means the switch is turned "on" and the unit should operate, if sufficient wind is available. This machine was upgraded to current design specifications in 1982 and has had an availability since then of 91%.

Another machine, the Enertech 44/25[3/] operated from 1982 until 1984 with an availability of 95%. The downtime included routine maintenance as well as repairs and abnormal conditions caused by icing. Clark and Vosper (1984) presented detailed descriptions of the repairs required for these machines and indicated that most repairs were needed on control systems. Many of the components have been deleted from later designs, thus reliability has been improved. A new Enertech 44/40[3/] which was installed in March and operated through October 1984, had an availability of 99.9%. The machine experienced no failures, and received only routine maintenance.

SYSTEM PERFORMANCE

The system performance of wind machines is determined from the electrical energy produced and the number of hours the machine operates. The Carter 25 was installed in August 1979 and was operated as a 240-V machine until January 1982. During this 2.5-yr period, the manufacturer made numerous design changes and modifications to the unit. In 1982, the unit was totally reworked to include all of the latest design modifications and the generator was changed to a 480-V system. During the 5-yr period, August 1979 to August 1984, the machine produced 141,111 kWh in 23,359 h of operation. This unit was actually on-line, producing power 53% of the time. After the unit was upgraded in 1982, it was available 91% of the time and was energized an average of 472 h or 64% of the time (Table 2). These data help to show the improvements in performance that have been achieved as wind machine technology has matured.

The performance data for the Enertech 44/25 are given in Table 3. This turbine was operated from July 1982 through January

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[3/] The mention of a trade name or model number is for reference only and does not imply an endorsement for use by USDA.

1984 and during this 19-month period, it produced 97,485 kWh of electricity. The unit averaged being on-line 470 hours per month or 64% of the time. This unit produced almost twice as much energy as the Carter 25 even though they had the same size generator. The swept area of the Enertech was 141 m^2 compared to 78 m^2 for the Carter; thereby allowing the Enertech to extract more energy in a given windspeed.

In March 1984, an Enertech with a larger generator was installed using the same rotor. The performance of this machine is given in Table 4. This machine had a rating of 40 kW and produced 49,476 kWh during the 7 months. The unit was on-line 3,218 hours or 63% of the time and had an availability of 99.9%. By increasing the generator size from 25 to 40 kW, the average output of the machine was increased from 10.9 to 15.4 kW while operating.

WIND RESOURCE PERFORMANCE

Any energy system that depends on the natural environment to provide its power is subject to times of abundance and times of scarcity. The dependability of the resource is an important element in the performance of the system that is often overlooked. Fig. 2 shows predicted annual energy production from an Enertech 44 as a function of average windspeed. The predicted energy was determined using a Rayleigh probability distribution and the power curve (AWEA, 1982). A 0.5-m/s increase in average windspeed can often mean a 10,000 kWh increase in annual energy production; therefore, it is extremely important that a wind turbine be placed in the location with the highest windspeed. Often the system performs well mechanically, but the overall performance is poor because of the location.

SUMMARY AND CONCLUSIONS

The performance of wind turbines with induction generators is dependent on the aerodynamic performance of the rotor, the operation of the drive train and control system, and the reliability of the wind resource. Induction generator systems require fewer controls than systems with variable pitch, thus, they have become the dominant system sold in 1984, comprising almost 90% of the sales. With fixed-pitch rotors, the pitch angle is a critical adjustment because it can alter the peak power by several kW and change the annual energy production by 10%. The pitch angle adjustment is used to optimize the energy production for a given average windspeed.

The reliability of the gearboxes, generators, and rotors, as well as the control system, has an important influence on the performance of the system. A wind machine operating for 5 yrs at Bushland, Texas, had an overall availability of 73%, but it had improved to 91% in 1984. A later design erected in 1982 showed an availability of 95%, and another unit operating for 7 months in

1984 had an availability of 99.9%. Maturity in the wind turbine industry is seen by these improvements. Today, some manufacturers are offering bonded assurance of at least 90% availability.

The performance of three machines, operated for a total of 86 months, clearly show that energy production is dependent on the wind resource and the dependability of the wind turbine. The turbines were on-line producing power 65% of the time and produced an average of 6.1, 10.9, and 15.4 kW for the Carter 25, Enertech 44/25, and Enertech 44/40, respectively. Using a power curve, average windspeed and the Rayleigh distribution, annual energy can be predicted with acceptable accuracy. These predictions are valuable in determining the best sites for units and evaluating the overall system performance.

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Table 1. Specifications of electrical wind turbines installed at Bushland, Texas.

	Carter 25	Enertech 44/25	Enertech 44/40
Manufacturer	Carter Wind Systems	Enertech Corporation	Enertech Corporation
Type	horizontal downwind	horizontal downwind	horizontal downwind
Rotor			
No. of blades	2	3	3
Diameter, m	10	13.4	13.4
Swept area, m^2	78	141	141
Rotational speed, rpm	120	53	57
Blade material	fiberglass	wood/epoxy laminate	wood/epoxy laminate
Airfoil, NACA	23015		
Transmission			
Type	double reduction, helical	triple reduction, helical	triple reduction, helical
Ratio	15:1	34.5:1	32:1
Generator			
Type	three-phase, induction	single-phase, induction	three-phase, induction
Rated power, kW	25	25	40
Output voltage, VAC	480	240	480
Tower			
Type	guyed pipe	free-standing truss	free-standing truss
Height, m	17	24.4	24.4
Performance			
Rated power, kW	25	25	40
Rated windspeed, m/s	11.6	13.4	13.4
Start-up windspeed	4.5	4.9	4.9
Cut-out windspeed	25	22.3	22.3
Rotor Speed Control			
Normal operating speed	aerodynamic stall	aerodynamic stall	aerodynamic stall
High windspeed shutdown	blade pitch change	control applies brake	control applies brake
Emergency rotor overspeed	blade pitch change	tip brake deploy	tip brake deploy

Table 2. Summary of performance data for Carter 25 wind turbine, Bushland, Texas, average air density was 1.08 kg/m^3.

Month	Carter 25				Windspeed @ 10 m
	Operating time		Energy produced	Avail-ability	
	hrs	%	kWh	%	m/s
June 1982	405	50	3,148	76	5.3
July	123	16	253	39	5.6
Aug.	423	59	1,481	98	4.6
Sept.	503	72	2,468	99	5.5
Oct.	418	67	2,300	100	5.5
Nov.	373	44	2,970	65	6.3
Dec.	255	36	2,343	48	6.8
Jan. 1983	451	59	2,574	100	5.2
Feb.	474	67	3,606	100	5.8
Mar.	526	70	4,224	100	6.2
Apr.	521	69	4,280	95	6.7
May	527	73	3,883	100	6.6
June	563	78	3,710	100	6.2
July	588	79	3,483	99	6.2
Aug.	463	60	890	81	4.4
Sept.	543	80	3,480	99	6.4
Oct.	583	78	3,387	100	5.8
Nov.	513	69	3,580	86	6.3
Dec.	546	69	2,905	100	5.9
Jan. 1984	494	71	2,806	99	5.8
Feb.	487	70	3,724	96	6.2
Mar.	487	63	3,110	99	6.4
Apr.	546	78	4,451	92	7.4
May	607	82	3,788	100	6.5
June	528	71	2,949	93	6.3
July	476	66	1,729	100	5.0
Aug.	335	47	492	100	4.1
Total	12,758		78,014		
Avg.	472	64	2,889	91	5.9

Table 3. Summary of performance data for Enertech 44/25 wind turbine, Bushland, Texas, average air density was 1.08 kg/m^3.

Month	Operating time		Energy Produced	Availability	Windspeed @ 10 m
	hrs	%	kWh	%	m/s
July 1982	474	68	4,947	100.0	5.6
Aug.	478	60	2,984	99.7	4.6
Sept.	525	73	4,536	99.9	5.5
Oct.	516	69	5,023	98.2	5.5
Nov.	441	61	5,292	97.9	6.3
Dec.	410	59	5,135	98.6	6.8
Jan. 1983	286	37	2,806	81.0	5.2
Feb.	344	49	3,642	76.1	5.8
Mar.	512	69	5,989	97.7	6.2
Apr.	476	64	5,922	100.0	6.7
May	537	68	6,769	100.0	6.6
June	539	75	5,959	100.0	6.2
July	584	79	6,290	100.0	6.2
Aug.	301	41	1,836	82.0	4.4
Sept.	474	68	5,823	81.0	6.4
Oct.	543	71	6,753	100.0	5.8
Nov.	469	65	5,979	92.0	6.3
Dec.	553	70	5,942	100.0	5.9
Jan. 1984	463	67	5,858	99.8	5.8
Total	8,925		97,485		
Avg.	470	64	5,131	95.0	5.9

Table 4. Summary of performance data for the Enertech 44/40 wind turbine, Bushland, Texas, average air density was 1.06 kg/m^3.

Month	Operating time		Energy Produced	Availability	Windspeed @ 10 m
	hrs	%	kWh	%	m/s
Apr.	570.5	82	11,148	100	7.4
May	567.5	76	9,087	99.7	6.4
Jun.	511.3	71	8,281	100	6.3
Jul.	430.0	58	5,017	100	5.0
Aug.	301.8	41	2,443	99.7	4.1
Sept.	460.6	64	7,240	100	5.8
Oct.	412.3	55	6,260	100	5.3
Totals	3,218.0	63	49,476	99.9	5.7

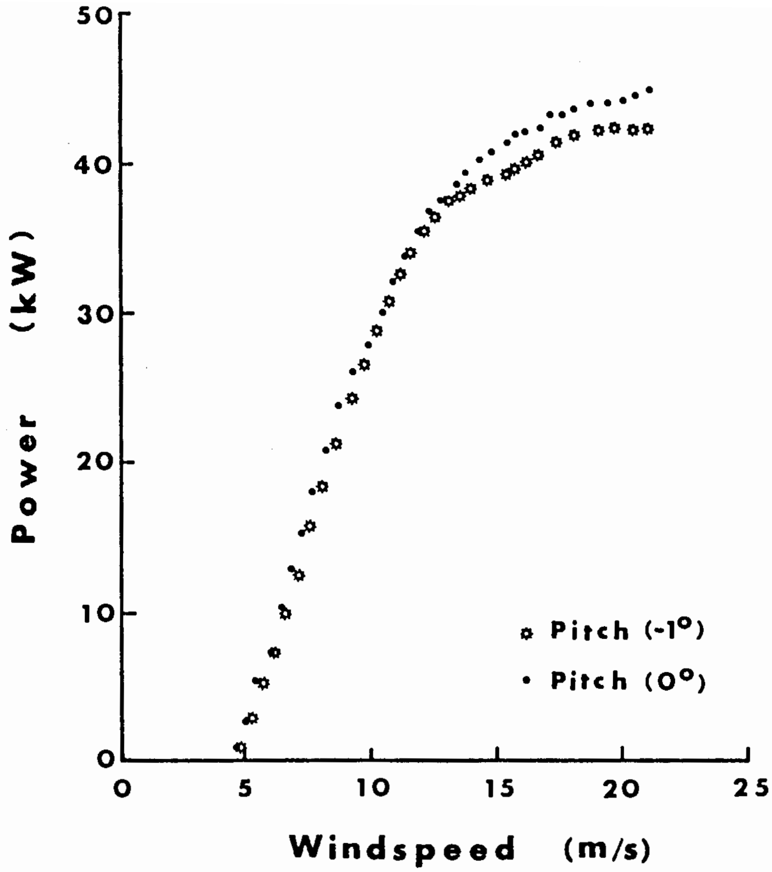

Fig. 1. Power curves for blade pitch of 0° and -1° (referenced to the blade-tip flat bottom, with respect to the rotor plane), corrected to standard air density.

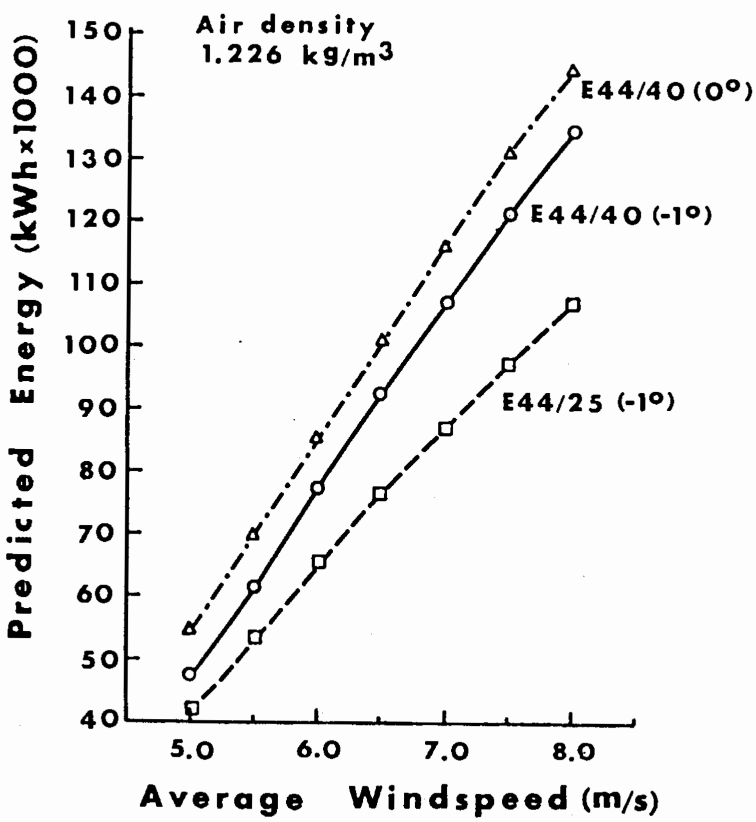

Fig. 2. Predicted annual energy production of the Enertech 44 with two generator sizes and two pitch settings. Standard air density of 1.226 kg/m^3 and availability of 95% were used.